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This final report describes the development, testing and utilization of an atomic oxygen beam apparatus, capable of energies ranging from approximately 4 eV to over 500 eV. The technique employed is that of creating a beam of negative oxygen ions, typically from electron impact on N_2O , then focussing and deceleration with subsequent electron photodetachment employing an argon-ion laser cavity with boosted power. Up to 30% of the ion beam may be photodetached at maximum laser powers, producing approximately 50 na of equivalent neutral flux. Angular divergence and energy spread are both well controlled and the total beam intensity is known to about 3 to 5%. Higher beam fluxes may be attained, but at the cost of filament and laser window lifetimes. Several measurements are described employing the beam apparatus in conjunction with a high stability quartz crystal mass monitor. Capabilities of the system have been demonstrated for studies of erosion, secondary charged particle production, and related work.

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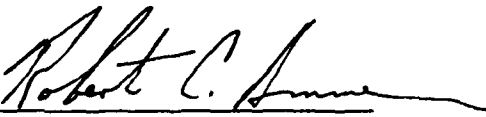
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ATOMIC BEAM STUDIES RELEVANT TO THE SPACE ENVIRONMENT

Department of Physics
University of Denver
Denver, CO 80208
30 July 1993


Robert C. Amme, Professor
Principal Investigator

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I. INTRODUCTION

Two major phenomena associated with low-earth orbit, i.e., surface glow and materials erosion, are attributable largely to the presence of residual atmospheric atomic oxygen. Roughly 70-80% of the remanent atmosphere (nominal pressure of $\sim 10^{-7}$ torr) results from photodissociation of O_2 , the remaining 20-30% being largely molecular nitrogen and O_2 . This residual atmosphere, which co-rotates with the earth¹, may typically possess local thermal velocities equivalent to ca. 600-900K. Thus, for eastward equatorial shuttle flights, surfaces in the ram direction experience an exposure to roughly 10^{14} OA/cm² sec, with impact velocity:

$$v_i = v_{orb} - v_c \pm v_t, \quad (1)$$

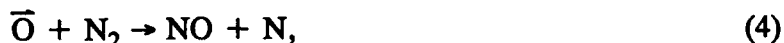
in which $v_{orb} \approx 7.8$ km/s, v_c = corotation velocity ($\sim .5$ km/s), and v_t is the normal component of the thermal velocity. For $\bar{v}_t = (8 kT/\pi m)^{1/2} = 1.1$ km/s, one has for O atoms

$$v_i = 7.3 \pm 1.1 \text{ km/s}, \quad (2)$$

and the associated energy is

$$E \approx 4.4 \pm 1.6 \text{ eV}, \quad (3)$$

wherein the spread represents a normal component equal to the average thermal velocity. A nominal 5 eV O atom can produce NO in the gas phase:



which in the center-of-mass system proceeds with a threshold energy of 3.4 eV. The presence of NO on ram surfaces, subjected to O-atom bombardment, is almost surely responsible for the major contribution to shuttle glow²:



The need to investigate gas-kinetic and surface-collision processes utilizing pure ground-state beams of atomic oxygen with energies of around 4 eV and above is thus apparent. An O-atom beam of proper collimation, purity, energy spread and energy range is of great value in studying a wide range of relevant collision processes. It was in this context that we planned to commit two years to the design and construction of our proposed facility, with the third year to be devoted to surface investigations utilizing quartz crystal oscillators to monitor mass changes under atom and ion bombardment. At least a preliminary investigation of surface optical emission from exposures to atomic oxygen was also planned for the third year. In addition, Dr. Czanderna (NREL) was to provide analyses of the exposed surfaces as regards to morphology and compositional changes using XPS(ESCA), ISS, AES, and FTIR as appropriate. Materials of interest, at least from our preliminary point of view, were silver, Kevlar, Kapton, and graphite epoxy.

II. PROJECT OBJECTIVES

A. Construction of a Neutral Oxygen Beam Apparatus

The central goal of this research has been to develop and test an atomic oxygen beam facility, with atomic beam particle energies ranging from approximately 4 eV to several hundred eV, and an intensity of $10^{12}\text{cm}^{-2}\text{s}^{-1}$ or better. The basic approach to the design of this apparatus follows concepts developed earlier³ in this laboratory for H-atom beam generation, except for modifications to the neutralization region made necessary by the influence of space charge at low beam energies.

It was recognized from the outset that the achievement of a useful beam of 4 eV neutral atoms would require very high quality ion optics with close tolerances, and would require provisions for adequate ion mass separation (OH^- is the nearest interfering negative ion). In our apparatus, collimation, mass filtering, and focusing are achieved at higher energies, followed by a slight (9°) electrostatic deflection. This is followed by a final deceleration just before neutralization. The assembly employs stainless steel (bakable) components mounted on precision ceramic rods and spacers (See Figs. 1 and 2). Space charge effects are of great significance only after focussing down to the final (4 to 5 eV) energy, at which point the O^- beam diameter will roughly double from space charge in a distance of about 8 mm. Thus, we sought and achieved a minimum ion beam diameter of about 1.5 mm at the neutralization region. The 9° deflection prior to final ion deceleration had been employed on our earlier H^- ion beam system³ to assure the absence of a fast background of neutrals and ion source photons.

Intense laser cavity radiation of visible lines from a 25-watt argon ion laser is used to photodetach electrons from the negative ion $\text{O}^-(^2\text{P})$. To determine the neutral beam intensity, the cavity radiation is mechanically chopped; the resulting modulation of the collected O^- ion current which escapes neutralization gives a measure of the neutralized component of the beam. A schematic of the optical and ion beam arrangement is presented in Fig. 3.

Measurements of beam energy spread and angular divergence were performed on the O atoms and O^- ions. Results for 25 eV are presented in Figs. 4 and 5; measurements on the O atom neutral beam are performed at energies sufficient to produce measurable secondary electrons.

The neutralized oxygen atoms must be 100% ground-state (^3P), with no accompanying impurities such as O_2 , driver gas, or photons arising from the ion source, wall collisions, or from other effects. To study O-atom interactions with surfaces, a high-sensitivity Leybold-Inficon quartz crystal mass monitor (QCM) has been employed, with a capability of measuring target mass changes of a

fraction of a monolayer (i.e., $\Delta m \sim 10^{-9}$ gram) over a time interval of several hours. While the O-atom intensities obtained in this device are much below those generally attainable by such techniques as plasma ashers or aerodynamic expansion nozzles, the compatibility of the system with ultra high vacuum and the complete absence of O_2 or metastable O make this approach especially unique. Moreover, the absence of large confinement magnetic fields allows for easier measurements of ion or electron currents and for easier access to the experimental section with argon ion gun, electron flood-gun, photocells, etc.

Emphasis has been given to long-term continuous operation of the beam in order to study the effects of oxygen bombardment of selected surfaces. As a result, the ion source is operated in a "conservative" fashion, i.e., lifetimes of the filaments and other components have been extended, but at some cost to the beam intensity. Seventy hours or more of continuous operation can be achieved by the use of $\sim 50\%$ argon as a buffer gas mixed with the N_2O source gas. Purchased originally from Colutron Corp., the ion source was modified considerably to extend its life and usefulness for use with oxygen. A paper describing this source has been prepared for publication⁴. Photographs of the entire system are presented in Fig. 7.

Two significant problems were encountered in our first efforts to operate the beam for prolonged periods under high vacuum. The first relates to laser mirror operation, while the second relates to the vacuum windows and their degradation when used in the presence of ultraviolet (laser bore light), high-intensity visible laser cavity radiation (488-514 nm), and vacuum conditions. These problems, and their resolutions, are described below.

B. Testing

1. Vacuum chamber tests.

Each of the three chambers: ion gun, beam shaping and focussing, and target chamber is separately pumped using Varian diffusion pumps supplemented with "Mexican hat" assemblies to minimize pump fluid back-streaming. Pumps on the first two chambers employ Corning 704 fluid, while the target chamber pump utilizes Santovac-5 fluid. The ion gun chamber pressure is typically ca. 10^{-6} torr, and the middle chamber operates at 10^{-7} to 10^{-8} torr. There is nearly complete separation of the target chamber from the middle chamber and, with moderate baking, target chamber pressures of ca. 10^{-9} torr can be sustained. Introduction of dry nitrogen gas ($P \approx 50$ -70 microns) in the foreline holds forepump oil backstreaming to negligible levels⁵. Careful examination of the Brewster windows by XPS and FTIR (see below) gave no indication of surface contamination after many hours of operation.

2. Laser cavity tests.

Because of potential difficulties with vibrations, optical alignments, and high losses, a multipass configuration⁶ using an enhanced output coupler and array of multipass mirrors was rejected in favor of elevating the intracavity power itself and employing but a single pass. It was found that this system provides relative ease in alignment and little difficulty with interference from forepump and other mechanical vibrations.

Prior to purchasing our 2040E Spectra-Physics 25 watt argon ion laser, some preliminary measurements were performed at the factory in order to determine how well the laser would perform at elevated cavity powers. These measurements, as well as subsequent observations in our laboratory, demonstrate that intracavity power levels can readily exceed 2.5 kW when the appropriate output-coupling mirrors are employed, using the multiline configuration (this is comparable to the intracavity power we have achieved for our H^- photodetachment apparatus which employs a 1.06 micron YAG laser).

The initial configuration employed a high-reflectance output coupler inside the target chamber, on the opposite side of the beam chamber from the Brewster window through which the laser light passed. A manipulator was designed so that mirror alignment could be achieved utilizing adjustment screws outside the chamber. It was found, however, that these mirrors were very susceptible to failure; products from several companies were tested and found to be adequate until the chamber was evacuated and the system was operated for several hours. Power densities, up to $170\text{kw}/\text{cm}^2$, were well below the levels prescribed by the manufacturers. To escape this problem, it was necessary to add a second Brewster window and reconstruct an adjustable mirror mount outside the vacuum chamber. The beam cavity chopper was also moved to the opposite side of the chamber (see Fig 3). No further mirror failures were experienced; the exact cause of this problem was not fully resolved.

Even though the addition of a second Brewster window reduced slightly the intracavity power, the resulting intensity in the photodetachment region was sufficient to neutralize up to 30% of the O^- ion beam. The neutralized fraction follows roughly a $1/v$ law, as expected from the ion traverse time. Percent neutralization as a function of cavity power is presented in Fig. 6, for which the O^- energy was 25 eV.

3. Ion beam characterization.

The final beam deceleration region employs an einzel lens located just after the 9° electrostatic deflection electrodes (Fig. 2). When optimally focussed, convergence of the beam into the neutralization region coupled with space-charge divergence yields a nearly parallel beam as the O^- ions pass through the laser cavity (normal to the paper). The O atom beam has been found to diverge at a half-angle of about 4.5° at 25 eV, with 95% of the current lying within this range (Fig. 5). The divergence changes only slightly at lower beam energies, as a consequence of the space charge, while divergence of the ion beam beyond the neutralization region continues to increase. The neutral atom beam flux can be determined by mechanically chopping the laser cavity (see Fig. 3) and using lock-in amplification³ to determine the resulting ac signal to the ion collector. A chopping frequency of 40 Hz is employed, producing a good square wave in the modulated current.

First measurements performed with the neutral O-atom beam were of the secondary electron yield from a (gas-covered) stainless steel target. The results, to be published, fall closely near the values expected from empirical arguments.^{7,8}

When initial tests of beam overlap and neutralization efficiency were completed, longer periods of operation were initiated to study mass changes of target surfaces, especially gold and silver films under high vacuum. It was then that we discovered an unusual, and hitherto unknown, phenomenon: under the combination of high vacuum and prolonged intense laser power, transmission of the fused silica Brewster windows began to diminish. After a few hours of operation the loss of transmission (ca 0.5%) was sufficient to spoil the laser cavity and neutralization efficiency was lost. Accompanying the loss was a reddish fluorescence that could be seen readily through a filter. The fluorescence appeared to be rather broad-band, centered near 660 nm. Upon admitting nitrogen (or even argon or helium) to a pressure of about 1 torr, the fluorescence immediately ceased. Further studies indicated that (a) the inner surface was not being contaminated with any measurable condensible substance (XPS and FTIR analyses yielded no carbon compounds), (b) ultraviolet radiation (non-lasing) from the laser discharge seemed to play a role (the window nearest the laser was found to fail more frequently), and (c) the quality of final polish seemed to be relatively unimportant, and (d) crystalline quartz windows behaved in approximately the same way (slightly longer times to failure were observed). Several different types of silica behaved similarly. Inquiries and discussions transpired with a number of authorities on laser damage at some leading laboratories

(Sandia, Livermore, University of New Mexico's Center for High Tech Materials, etc.) as well as with several optical polishing companies and with Spectra-Physics. Numerous different tests were performed with coated optics as well: silicon and aluminum nitrides and diamond-like carbon failed to prevent the degradation. Sapphire Brewster windows showed a bulk fluorescence and were too lossy to be useful, as was CaF_2 . Finally, in order to reduce the ultraviolet on the windows, a pair of mirrors that were highly reflective in the visible but not in the UV were installed in the external portion of the cavity, between the laser body and the windows (cf. Fig. 3). The UV is thus greatly reduced, and the operating period under high cavity power has been significantly extended. A paper has been published relating to this problem⁹. The work was also presented at the Oct. 1992 Laser Damage Symposium. To date, we have not found a complete explanation of the effect, but it is believed to be associated with broken bonds and (perhaps) a change in electrical conductivity and/or excited states of surface oxygen which are readily quenched collisionally when the vacuum is removed.

4. Molecular beam ionizer

For the preliminary studies of scattered atoms and molecules from surfaces, a high efficiency molecular beam ionizer was also constructed and tested. The design follows that earlier reported by Brink¹⁰, which employs an extended filament parallel to the beam direction and a cylindrical grid for ion trapping. Several grid sizes were studied and the source efficiency characterized as a function of geometry and operating conditions. This work is in preparation for publication¹¹.

C. Installation and Testing of a Quartz Crystal Microbalance

A Leybold-Inficon Model IC/4 Plus quartz-crystal microbalance was acquired and tested during the second year of this project. The associated controller can be accessed by computer and while its major commercial function is to permit the monitoring and control of added mass (by vacuum deposition, etc), it provides very high sensitivity to mass losses due to outgassing, sputtering, etc. as well. For long-term measurements in which dm/dt is very small, however, one needs to be concerned additionally with the clocking oscillator, built into the controller unit, which is vulnerable to thermal drifts in the laboratory in addition to those expected in the vacuum chamber. The latter drifts can be accounted for readily by operating a second reference crystal in the chamber, protected from the atomic beam. To provide for greater thermal stability over many hours of operation, we have modified the unit by referencing to a quartz crystal oscillator taken from an old Hewlett-Packard cesium clock, with a $\Delta f/f$ stability of $\sim 10^{-10}$ over several hours.

Preliminary measurements performed without the above modification were reported for O^- ions and O neutrals on silver-coated QCMs at the 1992 Air Force OSR workshop at Northwestern University. This work, while satisfactory, can be further improved upon with the modified system, and we plan to perform these additional measurements (using in-house funds) as resources permit.

Use of the microbalance to investigate low-energy sputtering from ion bombardment has also been made. A standard reference for physical sputtering of gold by Ar^+ at low energies is that by McKeown¹², who sought a threshold for the process.

D. Optical Emission Studies

Shortly after the beginning of our third year of effort (early 1992), a decision was made to give first priority to pursuing surface degradation studies, possibly at the cost of investigating glow phenomena. The reasons for this decision were twofold; first, considerable progress had already been made² in identifying some of the emission processes associated with atomic oxygen, and second, several laboratories had recently initiated efforts to develop protective coatings whose properties would need investigating. Further, it appeared that considerable study might be needed to solve the long-term window degradation problem, leaving insufficient time to pursue both efforts. As a consequence, full emphasis has been placed on our development of the quartz-crystal monitor for mass change measurements, and on the analysis of pre-exposed and exposed surfaces.

E. Surface Analyses of Oxygen-Bombarded Materials

Under a subcontract, this project has had available to it the facilities of the National Renewable Energy Laboratory, at Golden, Colorado. Dr. Alvin Czanderna, Senior Scientist and adjunct professor in our department, has been the co-investigator for this work. NREL's SIMS, XPS(ESCA), ISS, photomicrography, FTIR apparatus, argon ion gun, and spin-coating facility have all been utilized on this project. The ion gun was on loan to our laboratory and is installed in our target chamber; the remaining equipment was used at Golden, the samples being transported to and from that site.

Several surface analyses were performed on our degraded Brewster windows, as described above, in an effort to detect surface contaminants⁹. Studies were also performed on silver and gold-coated QCM crystals that had been exposed to several monolayer equivalents of 5 eV atomic oxygen. Some preliminary studies were performed on polymeric protective coatings provided by Drs. Jeffrey Gilman and Joseph Lichtenhan of the Rocket Propulsion Institute/Phillips Laboratory, Edwards Air Force Base. These initial coatings, applied at Edwards AFB to quartz crystals we provided, were found to be too thick (several

milligrams) for good adhesion and thermal stability in vacuum. Consequently, the weight change measurements were not useful due to prolonged outgassing and cracking. Thinner coats (on the order of 500nm) were prepared at NREL by spin-coating of the silsesquioxane-siloxane copolymer (designated by Edwards as JLP4-II) and characterized as to thickness and adhesion. Five samples were prepared for exposure to 5 eV O ions and to 5 and 15 eV O atoms. Since H_2O^{18} is available commercially, we can prepare beams of O^{18} , and perform XPS and other analyses of the exposed films for surface composition, thus discriminating between the O^{16} naturally present and the O^{18} from beam exposures. We are also investigating (under Research Corporation sponsorship) the prospects for assessing the relative surface effects of metastable O^+ ions vs. ground-state ions. This is possible because the fraction of metastable O^+ has been found¹³ to depend upon the source gas as well as ion source operating conditions. For example, O^+ produced from CO_2 can be 2% in excited states, while that produced from H_2O can be as high as 90%. At the present time, we are awaiting the availability of O^{18} -tagged CO_2 .

Should significant differences in reaction rates be found between O^+ and $(\text{O}^+)^m$ beam species at 5 eV, the importance of neutral O^m contaminants in O-atom beams (generated by means other than photodetachment of O^-) must be seriously considered in all such investigations.

This work is still ongoing (supported by institutional and other private funds); it is expected that the results will be published in collaboration with the Edwards participants.

III. PUBLICATIONS, REPORTS AND PRESENTATIONS

A. Publications

It is our expectation that a total of seven refereed publications will emerge from this three year (actually, 3.3 years with time extension approved) program. One of these, relating to damage of the Brewster windows, is published⁹ (reprints enclosed). This naturally preceded publication of a Review of Scientific Instruments article describing the entire apparatus; this article was held up when we found it necessary to investigate the long-term efforts of vacuum plus UV on silica windows.

As indicated in the above narrative, an ion source article⁴ is nearly completed which bears data on filament longevity and on negative (as well as positive) O-ion production.

A fourth article relating to near threshold-level sputtering measured by our QCM is nearly completed, as is the short article¹¹ characterizing our molecular beam ionizer.

Of high immediate priority is our ongoing effort with Edwards AFB personnel, using O^{18} to investigate the effects of fast O-atoms on the copolymer materials they have provided us. Finally, a seventh article will be submitted that describes secondary electron (more accurately, negative charge) production from bombardment of metal surfaces (copper and stainless steel) by O^+ , O^- , and O atoms neutrals. Much of this work has been reported at a previous AFOSR workshop.

An eighth article, relating to our QCM work with the erosion of silver by O atoms and ions as a function of energy, will eventually be published also. However, more data are still needed at the lower energies.

B. Reports

In addition to the extended abstracts prepared for our oral Contractors' Conference presentations and published by Northwestern University for the Air Force, we prepared as per agreement under the grant, a Progress/Forecast (7 mo.) in June 1990, our annual technical (interim) reports in December, 1990 and December, 1991. Because of our no-cost time extension, this final report, due originally at the end of the three-year grant period (December 1992), was delayed.

C. Presentations

This group presented a poster-session paper at the Northwestern University AFOSR Workshop on Surface Reactions in the Space Environment in September 1990. In the following years, oral presentations were made entitled:

Sept. 1991 (Northwestern): "Development of a 5-500 eV Atomic Beam Apparatus".

Sept 1992 (Skokie, IL): "Progress with the Denver O-Atom Beam Facility in Studies Related to the Space Environment".

Presentations were also made at the October 1991 Surface Chemistry Conference in Irvine, viz., the poster paper of same title as above, and an oral presentation entitled "Negative Charge Production from the Bombardment of a Copper Surface by Low Energy O atoms and Ions".

Additionally, Dr. Amme presented a colloquium to the Denver University Chemistry Department in January, 1992 entitled "Chemistry and Physics in the Sky," and a paper at the April meeting of the Colorado/Wyoming Academy of Science in Denver. Another paper is planned for August 19, 1993 at the annual meeting of the American Vacuum Society in Lakewood, Colorado, dealing with the beam facility and our preliminary measurements on secondary electron emission.

IV. STAFFING OF PROJECT

In addition to the principal investigator (Prof. Robert Amme), this project has been staffed by a number of individuals, whose essential contributions to its success are gratefully acknowledged by the writer:

A. Professional Research Staff

Dr. Bert Van Zyl, Research Professor
Dr. Thomas M. Stephen, Assistant Research Professor (formerly post-doctoral fellow)
Mr. Ronald E. Sturm, Senior Research Engineer
Dr. Alvin Czanderna, Adjunct Professor (NREL/SERI)

B. Technicians/Machinists

Mr. William J. Pont, Shop Manager/Instructor
Mr. James Bean, Research Technician
Mr. Charles Self, Machinist
Mr. Roy Simmons, Machinist

C. Graduate Students

Mr. Karl Wang (Ph.D. candidate)
Mr. Thomas vonderHaar (M.S.)
Mr. John Gibas (M.S.)
Mr. Vince Larson (M.S.)

D. Other Students

Marc Stadjuhar (Work Study)
Alan Lankford
Stephen Bottas

V. PLANS FOR FUTURE WORK

As described in II E and III above, we are continuing work this summer on the O, O⁺, and O⁻ bombardment of the Edwards AFB copolymers, with the objective of determining where the projectile O¹⁸ ends up in the exposed sample. Mass change as a function of beam energy is another objective; by varying the energy over a range of 4 eV to 40 eV or so, we hope to infer whether measurable thresholds exist for the observed processes (i.e., mass changes and O-atom accommodation in the material). This study is supported by Research Corporation and by internal funds. Depending on the success of this work, additional support will be sought from the Air Force or possibly another agency. Martin-Marietta Aerospace/Denver personnel have expressed interest in these studies, and may be interested in partially supporting similar work relating to their coatings.

An active proposal entitled "A Study of Energetic Oxygen Atom Reactions with Molecules Relevant to the Space Environment" was submitted to AFOSR on 30 July 1992; this work would relate primarily to gas-phase collision experiments, surface-scattering and surface reactions. The production of NO from O + N₂ collisions, and of OH molecules from O + H₂O are two important processes for the gas-phase studies, and NO and NO₂ product molecules from O+ surface collisions, with controlled surface adsorbate molecules at different surface temperatures, are of considerable interest.

We also have plans to assist NASA/Goddard personnel with calibration of O-atom detectors for satellite instrumentation. Drs. Fred Herraro and Mark Smith seek a high quality beam of 5 eV atomic oxygen, and have plans to travel here in late summer. Martin-Marietta/Denver has also expressed interest in various aspects of our beam facility; the writer has been invited to present a briefing there in late August.

Finally, as a consequence of attending the recent LDEF symposium at NASA/Huntsville in October 1992, we have made contact with three NASA labs with enduring interests in the materials degradation problem. We are continuing to seek alliances with those individuals.

VI. DIRECT COST SHARING

In our original proposal, we had indicated that the project, if undertaken, would be supported by a direct cost share from non-government funds totalling \$72,500 over the three-year program.

During the first year, a new Spectra Physics 2040E argon ion laser was purchased for the sum of \$64,245, and the University also provided at some cost a 3-phase, 480v 70 amp supply and terminal to power it. In the second year, the University provided us with a 386-based computer which is dedicated to the apparatus for data collection and beam monitoring (\$2920), and a second, similar computer for analysis work (\$1834). In the third year, we received a Varian leak detector (\$3,500 in private funds) plus \$8,000 in

support of graduate stipends (Mr. John Gibas and Mr. Vince Larson). The total cost sharing was thus well in excess of \$80,000.

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VIII. List of Figures

- Fig. 1 (a) Modified Colutron Ion Gun, with accelerator lens, and velocity filter
 (b) Ion beam steering and focussing assembly
- Fig. 2 Details of neutralization region, showing final deflectors D, ceramic rods A,B (one of three), securing pin C, and ion collection region E. Laser cavity is normal to paper and is represented by dot at intersection of axes FG, and H.
- Fig. 3 Overall arrangement of laser beam and ion/neutral beams.
- Fig. 4 Energy distribution of beam ions at 33 eV. The spread is fairly independent of beam energy.
- Fig. 5 Angular divergence of oxygen ion and atom fluxes, measured at 25 eV energy to utilize secondary electron production for detection of O.
- Fig. 6 Neutralization efficiency vs. laser cavity power at 25 eV ion energy. Efficiency varies as $E^{-1/2}$. Maximum cavity power attained is ~ 2.8 kW, with $\sim 31\%$ neutralization.
- Fig. 7 Photographs of Apparatus (left and right sides), looking from ion gun end.

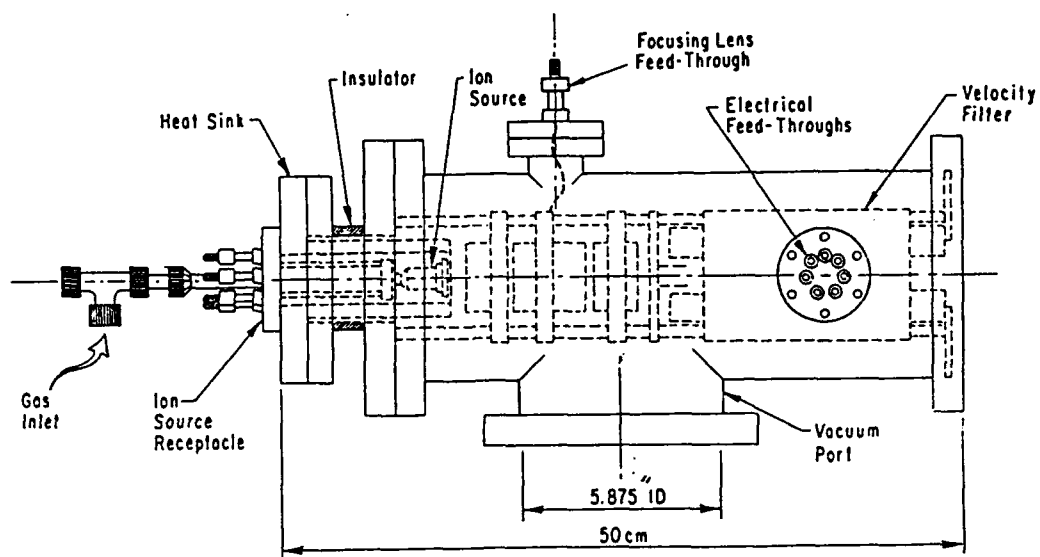


Fig. 1 (a)

Modified Colutron Ion Gun, with accelerator lens and velocity filter

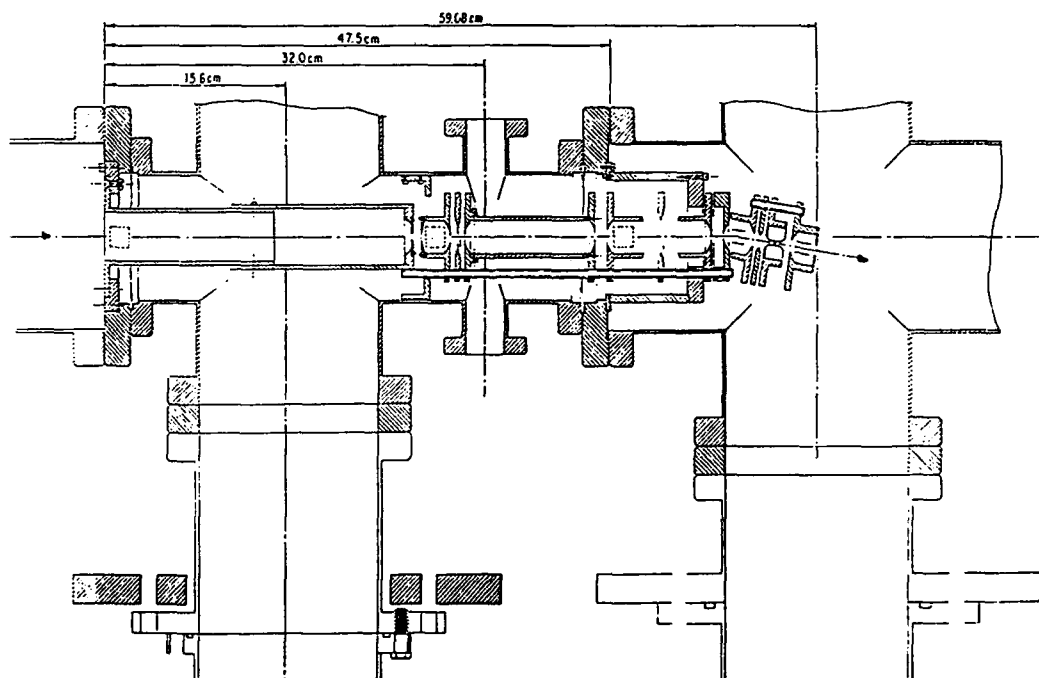


Fig. 1 (b)

Ion beam steering and focussing assembly

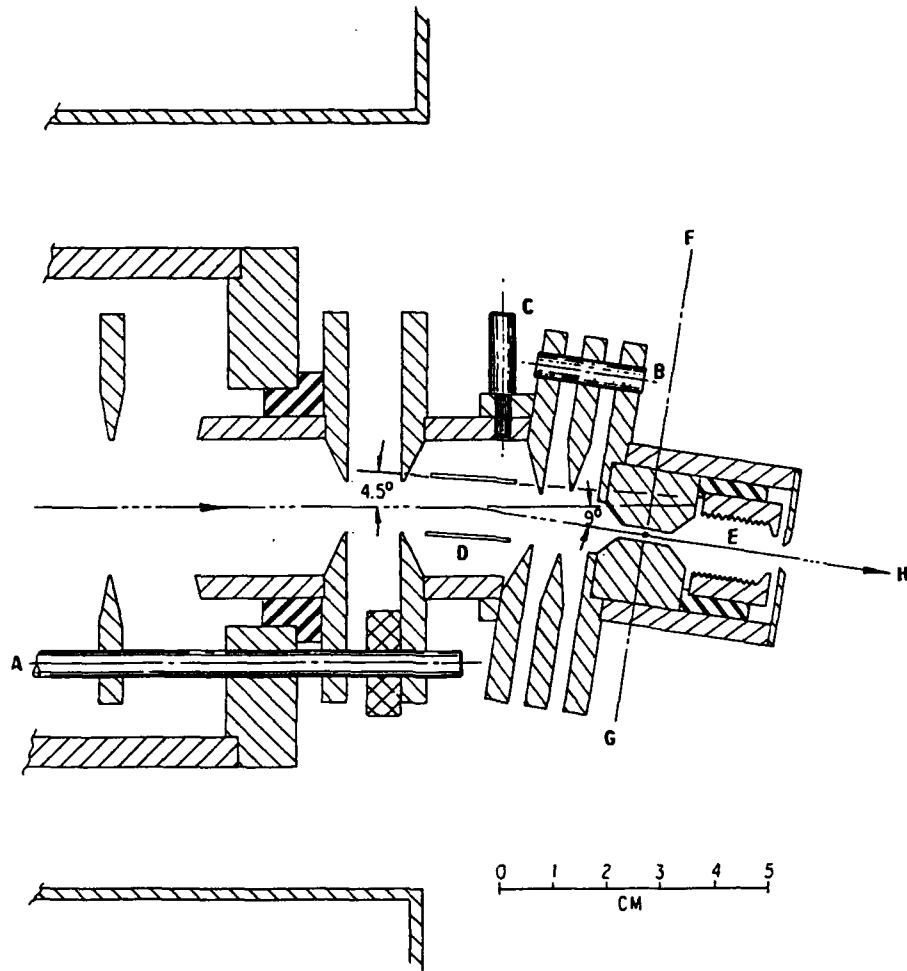


Fig. 2

Details of neutralization region, showing final deflectors D, ceramic rods A,B (one of three), securing pin C, and ion collecting region E. Laser cavity is normal to paper and is represented by dot at intersection of axes FG and H.

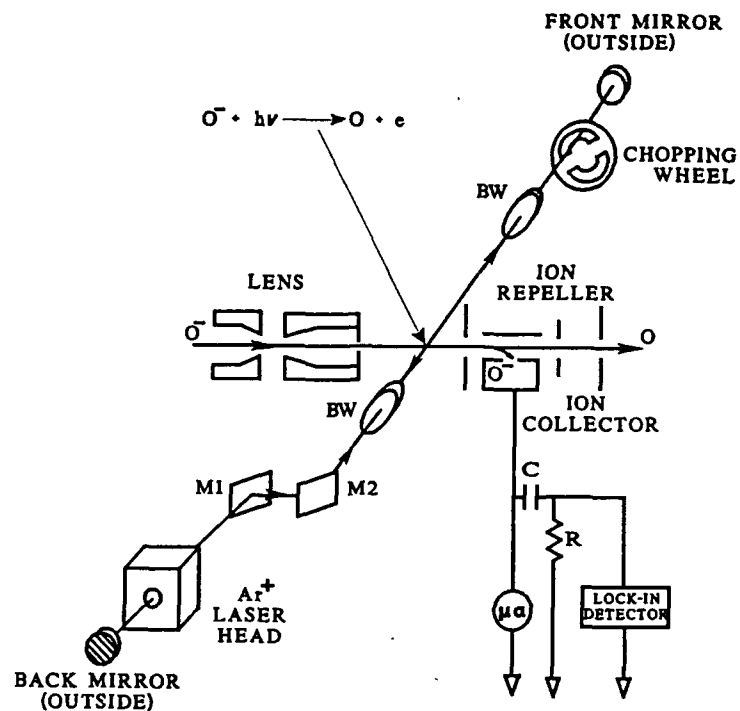


Fig. 3

Overall arrangement of laser beam and ion/neutral beams.

Energy Distribution of 33.2 eV Ions Compared with Gaussian (1.5 eV FWHM)

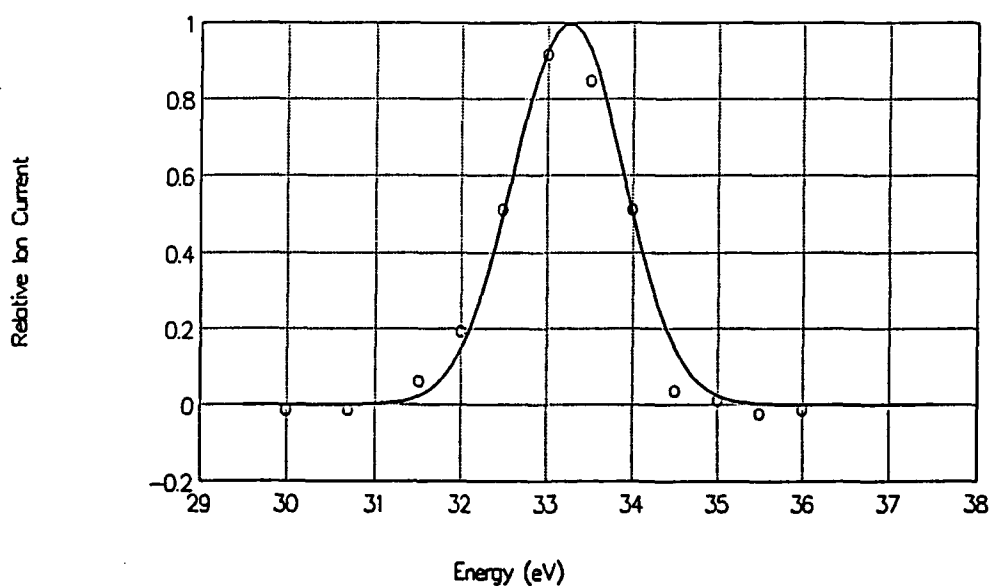


Fig. 4

Angular Divergence of Ion and Atom Fluxes at 25 eV Energy

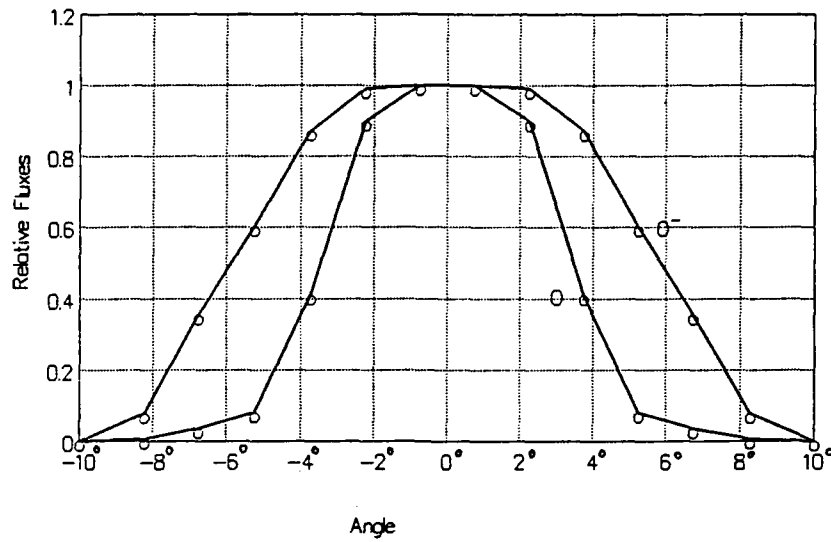


Fig. 5

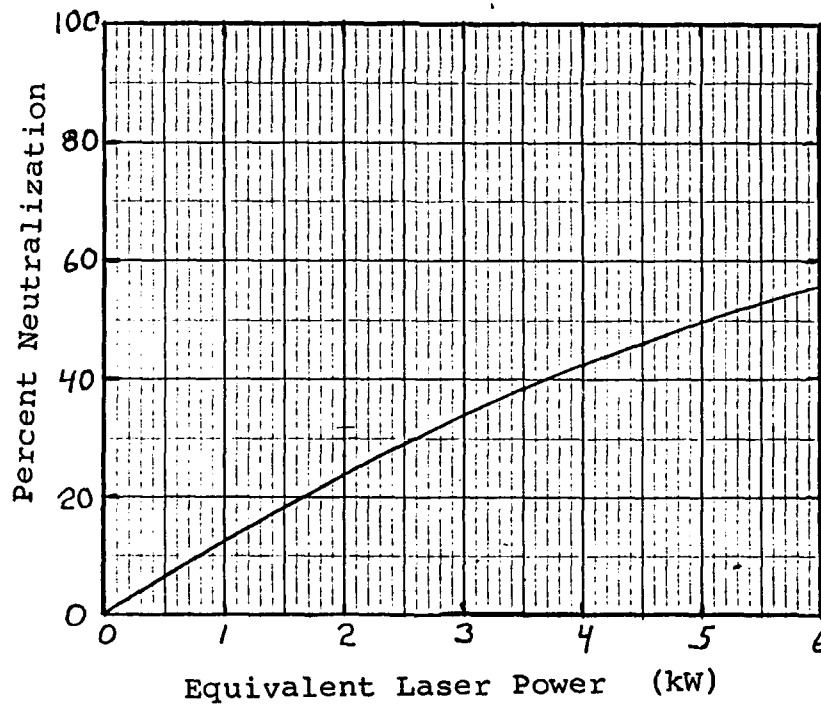


Fig. 6

Neutralization efficiency vs. laser cavity power at 25 eV ion energy. Efficiency varies as $E^{-1/2}$. Maximum cavity power attained is ~ 2.8 kW, with $\sim 31\%$ neutralization.

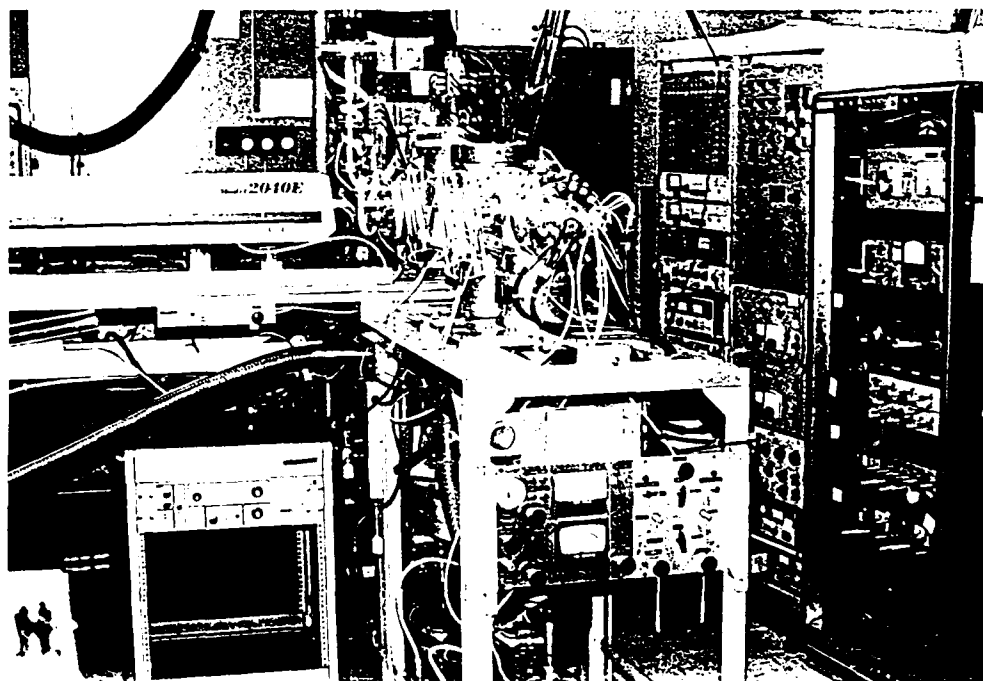
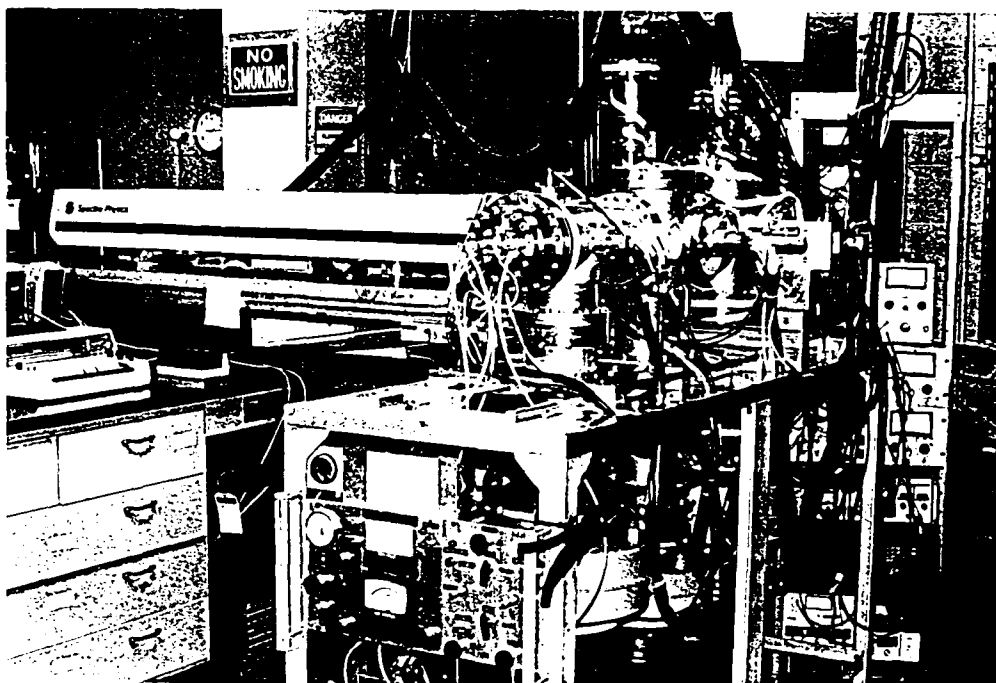


Fig. 7

Photographs of Apparatus (left and right sides), looking from ion gun end.